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Date: 25 May 1973

Project Title: "A Study of Microearthquakes in the Southeastern United States"

Project No: G-35-606

Principal Investigator Dr. L. T. Long

Sponsor: National Science Foundation

Agreement Period: From July 1, 1973 Until December 31, 1974

Type Agreement: Grant No. GA-31962 A#1

Amount: \$14,400 NSF
5,700 GIT (G-35-314)
\$20,100 Total

Reports Required:
Annual Progress Report or Final Report as necessary

Sponsor Contact Person (s):

Dr. Roy E. Hanson, Geophysics
National Science Foundation
Washington, D. C. 20550

Assigned to: School of Geophysical Sciences

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GEORGIA INSTITUTE OF TECHNOLOGY
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Date: 12-11-75

Project Title A Study of Microearthquakes in the Southeastern United States

Project No: 4-35-806

Principal Investigator: Dr. L. T. Long

Sponsor: National Science Foundation

Effective Termination Date: 12/31/74

Clearance of Accounting Charges: by 12/31/74

Grant/Contract Closeout Actions Remaining: Final Fiscal Report

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GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF GEOPHYSICAL SCIENCES

March 18, 1974

Atlanta, Georgia 30332
(404) 894-2857

National Science Foundation
Washington, D.C. 20550

Attn: Dr. Roy E. Hanson
Program Director for Geophysics

Subject: Annual Report covering period
Jan. 1, 1973 - December 31, 1973
Grant No: GA39162 A#1
Title: A Study of Microearthquakes in the
Southeastern United States
Principal Investigator: Dr. L. T. Long

Gentlemen:

The main objective of "A Study of Microearthquakes in the Southeastern United States" is to continue monitoring microearthquakes in known active areas of the southeast and to perform detailed studies of large southeastern earthquakes.

In line with this objective, Mr. John McKee, a graduate student, completed in September, 1973, a M.S. thesis titled "A Geophysical Study of Microearthquake Activity near Bowman, South Carolina." This investigation resulted in 3 well located microearthquakes and indications from gravity data that they may be related to a NW-SE trending basement structure similar to a 46 meter fault. Another graduate student, Mr. Edward Denman, is currently preparing a masters thesis on the geology and the historic and recent earthquake activity occurring near Clark Hill reservoir on the Georgia - South Carolina border. Unlike the Bowman area, the crystalline "basement" rocks are exposed, and interesting correlations of earthquake activity with exposed faults are developing.

Aftershock monitoring was attempted for two other southeastern events. The Florida event of October 27, 1973 yielded no recorded aftershocks. However, an attempt is contemplated to bring together existing data on this unique event. Aftershock monitoring of the Knoxville event of November 30, 1973 yielded over 6 events on a portable tape recorder and one smoked paper recorder. Monitoring by Georgia Tech was stopped after USGS and VPI representatives established a 6 element array. The Georgia Tech data was sent to the USGS for inclusion in their analysis. As soon as their results are available, we intend to re-evaluate our limited early data.

Event monitoring at Carters Dam has also resumed. While no natural events have been detected yet, the interest and support of the Corps of

National Science Foundation
Page 2
March 18, 1974

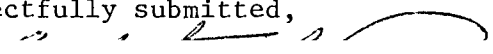
Engineers will now allow continuous monitoring until the reservoir is filled.

Computation of the spectra of selected southeastern earthquakes has been initiated by Mr. James Butler, a graduate student. Results are available now for only 15 events, but are encouraging in their potential to reveal corner frequencies.

Instrumentation has been augmented with the purchase of a new Sprengnether MEQ-800 from Georgia Tech internal funds.

I intend soon to propose a one year continuation of the microearthquake monitoring in order to finalize the study. There are at least two additional potentially active seismic areas in Georgia, which would be worthwhile studying in more detail. Also, in South Carolina the recent USGS seismic net is documenting the Charleston seismicity on a long term basis, not possible with smoked paper instruments. Consequently, additional study of that area would be contingent on a large event occurring and the availability of the array data. In addition, the spectral data need to be compared with the magnitude scale previously developed. Recent events should allow refinement of that scale to a point where it would be practical for application.

Respectfully submitted,



Dr. Leland Timothy Long
Associate Professor of Geophysics

LTL:gh

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GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF GEOPHYSICAL SCIENCES

December 30, 1974

Atlanta, Georgia 30332
(404) 894-2857

National Science Foundation
Washington, D.C. 20550

Attention: Program Director for Geophysics

Subject: Final Technical Letter Report

Principal Investigator: Leland Timothy Long, School of Geophysical
Sciences, Georgia Institute of Technology

Grant Numbers: GA31962 and GA31962A#1 extending from January 1, 1972
to December 31, 1974

Title: A Study of Microearthquakes in the Southeast United States

Dear Sir:

This final technical letter report is presented in two parts. The first part is a brief description of the research objectives and findings. Scientific collaborators, theses, and talks supported by the grant are presented in the first part. The second part is a first draft version of a hypothesis which explains the occurrence of earthquakes near Bowman and Summerville, South Carolina and which may be valid for most earthquakes in the southeast. A proposal to evaluate the hypothesis for the southeast in general will be sent with this letter report.

NSF support on these grants came at a critical time in the development of a geophysical program in Geophysical Sciences at Georgia Tech. The contribution of NSF support to the goals of the principal investigator and the success of the geophysics program is gratefully acknowledged.

Respectfully submitted,

Dr. Leland Timothy Long
Principal Investigator

LTL:bh

Final Technical Letter Report
National Science Foundation
Grant Number GA31962
December, 1974

A STUDY OF MICROEARTHQUAKES IN THE
SOUTHEASTERN UNITED STATES

PART I

Research Objectives and Findings

Objectives

The objective of the research supported by the grant was to attempt to record microearthquakes in areas of known historical seismicity or potential risk in the southeastern United States. In areas where significant activity was identified or a large earthquake occurred, more detailed seismic studies were to be performed and the data compared to other geological and geophysical data.

Findings

In general the research supported by the grant has shown that microearthquakes can be detected in the southeastern United States. However, their occurrence rate is significantly and often frustratingly lower than typically observed in more active areas. This experience has led to the application of other available geophysical tools in a more comprehensive study of suspected epicentral zones. These studies have shown a correlation between earthquake epicenters and high-velocity, high-density rigid geologic units in the crust, particularly near Bowman and Summerville, South Carolina.

This association suggests a mechanism which can generate abnormal stresses and hence foster earthquakes. The critical factor appears to

be the geometry of the more rigid units which because of their rigidity will bear most of the stress load. Earthquakes should occur near points in the geometry of the rigid units susceptible to stress amplification on application of regional or local stress. Considering the amplification, low level stresses like those associated with regional uplift or the reaction to isostatic inequilibrium will be sufficient to activate earthquakes. This hypothesis offers an explanation for the Charleston earthquake and may lead to a method of predicting whether and where similar events may occur in the future.

The research has involved a number of investigations into various aspects of southeastern United States seismicity as opportunities would allow. The findings are perhaps less significant than the hypothesis above for earthquake tectonics in the southeastern United States. Many findings have been presented in the publications or talks supported by the grant. The following is a summary of these intermediate findings.

General Seismicity Studies

A magnitude relation was developed for the southern Appalachians and the southeastern United States. The results are shown in figure 1. The relation showed significant deviations from the usually assumed smooth decay rate with distance. There was an azimuthal variation amounting to an amplification factor of more than three on strike with the Appalachian structures. There were also abnormally high-amplitude zones at multiples of about 250 kilometers which might explain some of the intensity halos observed in southeastern United States intensity maps. These high-amplitude zones can be explained by shear wave reflections from the Moho and near-surface attenuation. Quarry explosions were used for distances less than 150 kilometers (ATL only). They show a

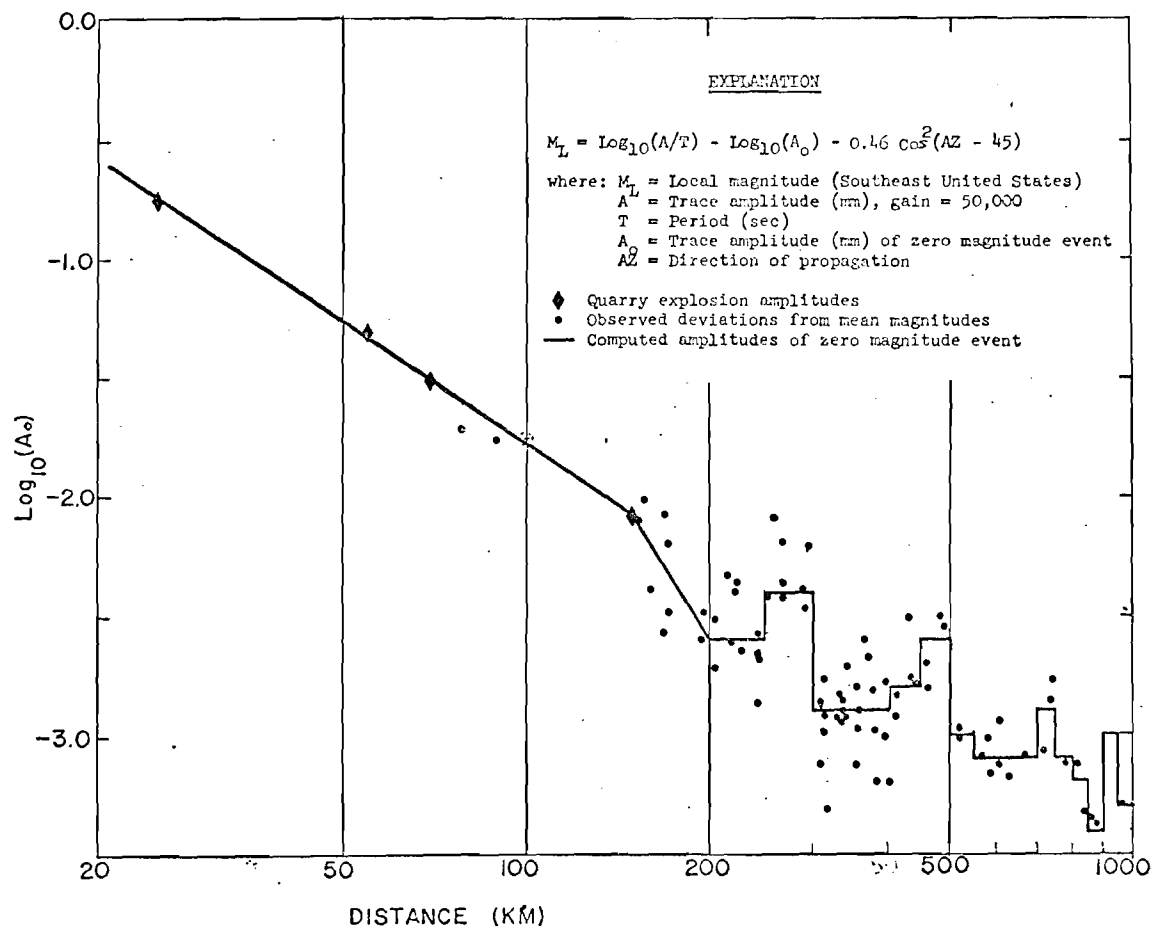


Figure 1. Magnitude relation for the southern Appalachians.

consistant relation between charge size and trace amplitude when the partition between Love and Rayleigh surface wave excitation is accounted for. The use of Quarry explosions in this way may be useful in predicting seismic intensities on a regional basis.

Studies of sequences of events indicate that "b" values in the southeast United States vary with magnitude and location. This further suggests that southeastern United States earthquakes may originate from varying conditions of ambient stress. Consequently, extrapolations of parameters derived from microearthquake data to larger magnitude events are not reliable.

Study of Bowman, South Carolina Earthquakes

The South Carolina earthquake of February 3, 1972, was located at 34.46°N, 80.58°W, approximately 27 kilometers east of Orangeburg. It occurred at 6:11 p.m. EST (23:11:08.24 GMT) with a magnitude (m_b) of 4.5 within a range of 0.2 units. Macroseismic data show a maximum intensity (MM) of V in Bowman and Cameron, South Carolina, and a total felt area of 26,000 square miles. The Bowman epicentral area has experienced a continuing sequence of aftershocks and these have been the object of more detailed investigations. Between August 8, 1972 and July 1, 1973 at least seven microearthquakes were recorded with epicenters near Bowman including three recorded at three or more stations in a local tripartite array. Gravity data have delineated a linear northeast-southwest diabase unit in the basement. The dike-like unit in the basement is nearly 6 kilometers thick at the basement surface. Its seismic velocity is in the range of 6.1 to 6.9 km/sec implying that the rocks are more rigid than normal crustal rock. Northeast of Bowman and coincident with two of the epicenters determined from array data the

rigid unit thins. It is proposed that this thinning of a more rigid member of the crust will create a zone in which ambient stress can be amplified. The origin of the ambient stress may be related to recently observed vertical crustal uplift. Furthermore, there is some evidence in gravity data of a northwest-southeast trending apparent displacement structure in the basement which could be interpreted as evidence for post-Cretaceous crustal movement. This northwest-southeast structure intersects the diabase near the epicenter of the recent earthquakes. Trends in the magnetic data support the existence and possible extension of the northwest-southeast structure. The northwest-southeast trend would be correct for a fault in a northeast-southwest rigid crustal unit which was stressed on bending of the crust in a manner compatible with recent uplift data.

Florida Earthquake Evaluation

The Florida earthquake of October 27, 1973 had a macroseismic location at 28.1°N, 81.25°W, about 39 kilometers south of Orlando. It occurred at 06:22 GMT and its magnitude (m_b) was 4.0. The early morning occurrence prevented evaluation of the intensity I-II felt areas. However, it was felt with intensity III-V over 25,000 square kilometers of central and eastern Florida. A correlation of historic epicenters with Bouguer anomaly trends implies that earthquakes in Florida occur near the extensions of the edges of crustal blocks.

Clark Hill Reservoir Studies

Following the installation of the ATL WWSSN station in 1963 at least twelve events with magnitudes greater than 2.5 (M_L) have occurred in the Clark Hill Reservoir area. Prior to the August, 1974 earthquake with

magnitude ≥ 4.5 the area exhibited a low-level of seismic activity with epicenters scattered throughout about 1000 square kilometers centered in the reservoir area. The occurrence rate indicated a high b value (1.3) and often the characteristics of earthquake swarms. Following the August, 1974 earthquake many earthquakes have occurred (thousands in the -1.0 to -3.0 magnitude range) but none to date has been located outside the immediate epicentral zone.

A study of the geology of the Clark Hill Reservoir area which combined existing literature with new gravity and magnetic field data indicates complex structural relations between the more rigid metadacites, basic dikes and amphibolites and the less rigid gneisses, schists and phyllites. Two fault systems were identified in the geologic data. One is a series of northwest-southeast trending faults with "surface" displacements of 200 to 2000 feet. To the southeast near Belair, Georgia a thrust fault with a similar trend offsets formations of Late Cretaceous age. However, these faults in the Clark Hill Reservoir area can also be interpreted as Pre-Cretaceous. The second fault system is a (Late?) Paleozoic shear zone trending northeast-southwest. This shear zone is made up of a button schist and was the epicenter of the one microearthquake located in four attempts to record events with a tripartite array and magnetic tape.

During the more than 80 noise-free days of recording in the Clark Hill Reservoir area numerous quarry explosions were identified and they indicate a 8.0 km/sec distance relation for S-P times (i.e. $V_p = 5.85$ km/sec for a Poisson ratio of 0.25). Approximately nine microearthquakes were recorded with a single instrument approximately one year prior to the August, 1974 earthquake. A difference in the character of many of these

events is evident in the ratio of P to S amplitudes, but the cause of this variation has not yet been identified. No significant relation between seismicity and variations in the reservoir level was noted.

Aftershock monitoring of the August 2, 1974 event has yielded 27 days of tripartite smoked paper data with literally thousands of earthquakes. Tape data is available for part of this time. Unfortunately, a tape unit adapted for portable application over the epicenter was stolen before the data could be retrieved. The remaining data has yet to be analyzed. A continuation of the analysis supported by the AEC will attempt to relate these events to a detailed investigation of the epicentral zone and continue to monitor events in the region.

Publications

Long, Leland Timothy (1972). The South Carolina earthquake of February 3, 1972, Earthquake Notes, Vol. 43, No. 2, pp 13-17.

Long, Leland Timothy (1974). Earthquake sequences and b values in the southeast United States, Bull. Seis. Soc. Am., Vol. 64, No. 1, pp 267-273.

Long, Leland Timothy (1974). The Florida earthquake of October 27, 1973, Earthquake Notes, Vol. 45, No. 4, (in preparation).

Thesis

McKee, John H. (1973). A geophysical study of microearthquake activity near Bowmen, South Carolina, Master's Thesis, Georgia Institute of Technology, Atlanta, Georgia, 72pp.

Denman, Harry Edward (1974). Implications of seismic activity at the Clark Hill Reservoir, Master's Thesis, Georgia Institute of Technology, Atlanta, Georgia, 103 pp.

Papers Presented at Meetings

Long, Leland Timothy, "Local magnitudes and recent earthquake activity near the Georgia-South Carolina border," Eastern Section SSA, Penn State University, October 7, 1971.

Long, Leland Timothy, "A local magnitude scale for the southeast United States," Southeastern Section GSA, Knoxville, Tennessee, April 13, 1973.

Long, Leland Timothy and John H. McKee, "A microearthquake survey near Bowman, South Carolina," SSA, Golden, Colorado, May 18, 1973.

Long, Leland Timothy and Harry E. Denman, "The Georgia-South Carolina earthquake of 2 August 1974; foreshock survey and macroseismic effects, Eastern Section SSA, Cambridge, Massachusetts, October 10, 1974.

Long, Leland Timothy, "A model for the earthquake tectonics of the Bowman and Summerville, South Carolina epicentral zones. Southeastern Section GSA, Memphis, Tennessee, April, 1975.

Collaborators

The research supported by the NSF Grant has encouraged a cooperation and interchange of data with investigators at other southeastern universities and at other government agencies including the U.S. Geological Survey, NOAA, and the A.E.C. This interchange of data and ideas would not have been possible otherwise. The research has also helped develop a local reputation in geophysics for the School of Geophysical Sciences. This reputation has generated numerous newspaper accounts and interviews which have perhaps enhanced the public's understanding of local seismicity.

Grant funds have provided direct support for at least twelve students at Georgia Tech. Five were graduate students of which two wrote theses on research work related to the Grant. Eight intend to or have obtained employment in geophysics.

The students are as follows:

John McKee (graduate research assistant) completed his M.S. thesis in June, 1973 and currently works in explorative geophysics. His thesis work on the Bowman microearthquake was a significant contribution to the research.

H. E. Denman (graduate research assistant) completed his M.S. thesis in December, 1974 and is currently working as a geologist-geophysicist with Dames and Moore. His thesis work on the seismicity of the Clark Hill Reservoir area provided unique data prior to the large ($m \geq 4.5$) event in August, 1974.

S. R. Bridges (student assistant and graduate research assistant) initiated aftershock studies in the Clark Hill Reservoir area. He intends to work this data into a M.S. thesis. Continued work in the Clark Hill Reservoir area is supported by the AEC.

J. Butler (graduate research assistant) developed a computer program to process spectral data of earthquakes. He has also worked on a monitoring program and an associated geophysical survey at Carters Dam, Georgia. This work which initially was supported by this grant is now nominally supported by the U.S. Army Corps of Engineers.

N. L. Faust (graduate research assistant) provided field support for many studies on the grant. He is currently preparing a M.S. thesis in remote sensing of geological features using ERTS data. He is now employed full time in the Engineering Experiment Station, Georgia Institute of Technology, to help develop a program for application of space data.

L. D. Brown and H. B. Clark (student assistants) were undergraduate physics majors who have gone on to graduate school in geophysics at Cornell and Virginia Polytechnic Institute respectively.

R. L. Garfield (student assistant) was a physics major who intends to work as a geophysicist.

C. F. Revell, H. W. Bruce, and D. B. Weisenhorn (student assistants) were students in electrical engineering who assisted in building and repairing the instruments.

Comments

When this study of microearthquakes in the southeastern United States was initially conceived perhaps only three seismic stations were operating effectively in the southeast and only the larger events had been recorded. Few studies were being performed. Today, a net of nearly eight stations covers the important South Carolina seismic zone and a net is planned for North Carolina. In Georgia, a permanent station was established at Americus, a temporary station at Carters and an array is planned for the Clark Hill Reservoir area. The only real loss is the closing of station ORT in Tennessee. Many of the previous difficulties in locating epicenters and detecting smaller events no longer exist except for the rare Florida events. Consequently, the need of portable recorders in the location of active areas no longer exists. Instead they can now be used much more efficiently to perform detailed studies of known active areas or after-shocks in the style of the complete geophysical study initiated in the Bowman area.

The research supported by this grant has directly or indirectly supported or initiated a significantly expanded study of seismicity in the southeastern United States. The grant research in the Bowman area was performed before and during the establishment of the South Carolina net, although we did not find out about the installation of the net until after our work in Bowman was complete. If the data from the net can be made more accessible a search of the records is planned for recent events in the Bowman area in order to further evaluate a tectonic model for that area. The preliminary study of the seismicity in the Clark Hill Reservoir area will be continued in expanded form under sponsorship of

the AEC. The monitoring near Carters Dam has been continued by support from the U.S. Army Corps of Engineers.

The magnitude studies initiated in this grant suffered from lack of data. With time and increased station coverage enough events may be recorded to allow expansion of the analysis and perhaps justify a relation between the attenuation function and expected intensities. Finally, the research supported by the grant has indicated a tectonic model which can explain the occurrence of earthquakes in the southeast. I am proposing an evaluation of this hypothesis in a subsequent grant.

Final Technical Letter Report
National Science Foundation
Grant Number GA31962
December, 1974

A STUDY OF MICROEARTHQUAKES IN THE
SOUTHEASTERN UNITED STATES
PART II

A proposed publication entitled:

A HYPOTHESIS FOR THE OCCURRENCE OF
EARTHQUAKES IN THE SOUTHEAST UNITED STATES

Abstract

Earthquakes occur in the southeastern United States because the geometry and strength of crustal units with anomalous rigidity fosters the concentration of stresses when the crust is deformed or stressed. The correlation of epicenters near Bowman, South Carolina with a thinning in a rigid (i.e. anomalously high velocity) geologic unit of the crust supports this hypothesis. The hypothesis is also supported by similar associations near Charleston, South Carolina and a general association in Georgia and South Carolina of earthquakes and regions with high gradients in the Bouguer gravity anomalies. The geometrical concentration of stresses implies that stresses adequate to cause earthquakes can be derived from any one of a number of existing sources. These include the isostatic response of the crust, flexures of the crust related to regional uplift, and regional stresses or their secondary manifestations derived from the mechanisms of plate tectonics. Measurements of crustal movement and measurements of the velocity structure and shape of major geologic units in the crust could be used to delineate where earthquakes are likely to occur in the southeastern United States.

A HYPOTHESIS FOR THE OCCURRENCE OF EARTHQUAKES IN THE SOUTHEAST UNITED STATES

Introduction

A definitive relation between recent seismic activity and some observable tectonic feature in the southeast United States has to date eluded investigators. Neither the unusually large 1886 Charleston earthquake nor the smaller events with epicenters in the Appalachian Mountains and in a transverse zone extending southeast through South Carolina have been definitely associated with major tectonic features or known faults. Also the southeast United States lies on the interior of the North American Plate. Consequently, the known mechanisms of seismicity associated with plate edges or active established faults do not directly apply. While the occurrence of seismic activity in the interior of plates can be partially explained by the existence of regional stresses originating at the boundary of the plates, the apparently incoherent spatial distribution of epicenters and the variety of earthquake fault plane solutions where known (e.g. Street et al., 1974) has not been explained. The object of this paper is to illustrate how major geologic units in the crust and variations in crustal structure in the southeast United States can explain the occurrence of earthquakes.

Physical Models for Stress Amplification

The fundamental hypothesis to be presented in this paper is that earthquakes occur in the southeastern United States because irregularities in crustal rigidity and crustal strength foster the concentration of stresses in a deforming crust. The geometries of the crustal structures with anomalous rigidity and strength are determined primarily by

the geometries of the major geologic units in the crust. Surficial sediments like the post-Cretaceous Coastal Plain sediments would have only a minimal secondary relation with earthquake occurrence. The positions of the crustal geologic units are determined by the contact zones between coherent crustal blocks or lateral irregularities within crustal blocks.

A simple model which bears similarity to the crustal structure in the epicentral regions of recent earthquakes near Bowman, South Carolina, consists of a high-velocity, high-density linear vertical intrusive (see Figure 1). The intrusive is near the contact of two coherent crustal blocks of different thickness and it has an abnormally thin zone near this contact. The crust, as is the case of South Carolina, is experiencing an apparent bending (Meade, 1971) which Bollinger (1973) has previously surmised as related to earthquake activity. Because of the existence of a boundary between crustal blocks and the inherent irregularity of this boundary, the bending stresses will be modified and perhaps amplified in the vicinity of the boundary. Near the thin spot in the intrusive, stresses in the rigid member will be amplified. Block-edge stresses (Artyushkov, 1974) may also augment the local distribution of bending stresses. Consequently, stress levels sufficient for the generation of earthquakes will most likely be found near boundaries between crustal blocks or where a rigid unit thins and is the weakest. Based on shear wave velocities, rigidity of the rocks in a basic intrusive (e.g. diorite) can be 30 percent greater than the rigidity of the surrounding rocks. Consequently, on bending this part of the crust, the rigid units will absorb and concentrate stress within the crust. For an equal strain the more rigid rock

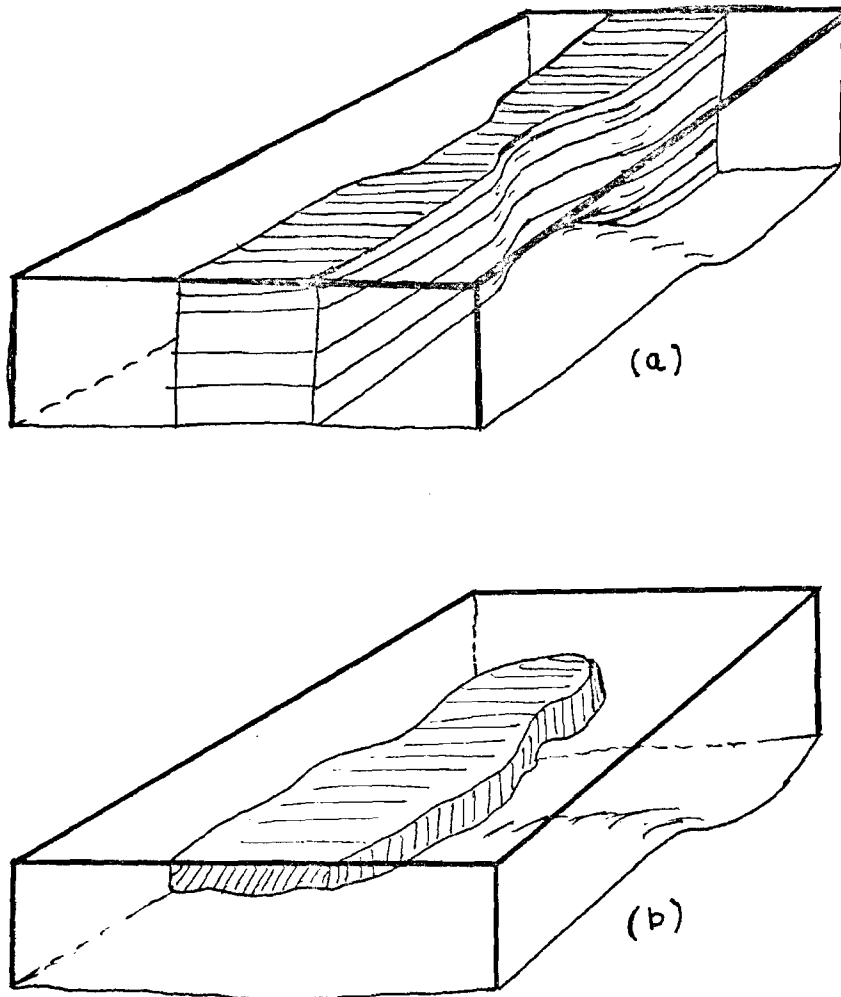


Figure 1. Models of rigid structures which would be susceptible to stress amplification because of their geometry. Model (a) is similar to the presumed structure near Bowman, South Carolina. Model (b) is similar to the presumed structure near Lincolnton, Georgia.

member will bear most of the stress. Hence, earthquakes in this model will most likely occur near or in high-velocity crustal units at their intersections with boundaries between crustal blocks or where their geometry can cause the greatest concentration of stress.

While this model satisfies the general crustal structure near Bowman it is certainly not the only possible geometry that can concentrate stresses. The end or terminus of a rigid unit (Figure 1b) is also susceptible to a geometrical amplification of applied stresses. The 1886 Charleston earthquake and recent events near Summerville have epicenters near the eastern or northeastern terminus of a high-density and perhaps rigid geologic unit in the crust. Near Lincolnton, Georgia, in the general epicentral area of an intensity VI earthquake in 1875, a possible responsible high-velocity unit is a thick metadacite sill (Denman, 1974).

Evidence for the Hypothesized Model in the Southeast United States

The most important determinative factor in establishing the epicenters of earthquakes in the hypothesized southeast model for intraplate tectonics is a rigid crustal unit with a geometry capable of concentrating regional stress. Any other structural irregularity which could foster the local perturbation of stress, such as boundaries between coherent crustal blocks, will increase the probability that the ambient stress levels will exceed the local shear strength. The historical seismic activity has the general character of scattered epicenters and a limited number of currently active zones. Associations of activity with linear features have been attempted (Straley, 1966) but have not proved conclusive. It is also significant that none of the observable Paleozoic

shear zones have yet shown more than an incidental correlation with seismic activity.

One way of evaluating an association with rigid units and structures geometrically susceptible to fracture would be to compare the occurrence of earthquakes to the observed gravity field. The Bouguer anomalies associated with rigid crustal units such as basic intrusives are typically positive and in the southeast United States can range up to +50 mgals. The Bouguer anomalies associated with boundaries between coherent crustal blocks which might perturb the stress field can be of two types. The first are anomalies associated with the termination or change in geologic structures of differing density near the boundary. The second is a change in the regional Bouguer anomaly caused by a contrast in layering or thickness between the two crustal blocks. Consequently, the Bouguer anomalies to be expected near the more rigid geologic units and the boundaries between coherent crustal blocks will typically exhibit large gradients. These same areas will be more likely to possess geometries capable of concentrating regional stress, such as a thinning along strike or the termination of a structure. Because the hypothesized model associates earthquakes with rigid units and because the probable occurrence of large stresses increases near junctions with crustal boundaries, earthquakes should be associated with zones of high gradients in the Bouguer gravity anomalies. However, high gradients will be associated with an entire geologic unit as well as with most boundary zones. Hence, the existence of a gradient does not, by this hypothesis, imply a potential for earthquakes, whereas the absence of a gradient would imply a reduced potential. Figure 2 shows the superposition of epicenters on a map of the magnitude of the first derivative of the Bouguer gravity anomalies



Figure 2. Magnitude of the gradient of the Bouguer gravity anomaly.
Gravity data were gridded at an 8 km separation.

in Georgia and western South Carolina. Gravity data were gridded at an eight kilometer interval and a centered finite difference approximation to the first derivative and was used so that the effective minimum wavelength observable is 16 kilometers. Considering the precision of the epicenters for historic data to be as much as ± 25 kilometers, few events in Figure 2 occur more than the 25 kilometers expected error distance from a high gradient zone. Many occur near the end of a high gradient zone. Similar relations for the midcontinent regions have been noted by McGinnis and Leeds, 1974 and McGinnis and Ervin, 1974.

The hypothesized association of earthquakes with more rigid geologic units such as basic intrusions is supported by detailed studies of aftershocks of the Bowman, South Carolina February 3, 1972 earthquake (McKee, 1974). Near Bowman, South Carolina (see Figure 3) microearthquakes were located on the northwest edge of a six kilometer wide vertical major geologic unit which strikes $N40^{\circ}E$ (McKee, 1973). Other events recorded with a single portable instrument could have epicenters compatible with these locations. The unit exhibits a density contrast and velocity (6.6 km/sec) consistent with an interpretation of it as a basic intrusive such as gabbro. Its anomalously high velocity would imply a rigidity which was nearly 30 percent higher than in the adjacent rocks. The interpreted rigid structure extends to the southwest approximately 15 kilometers. To the northeast at a distance of about 20 kilometers it joins a larger and more extensive region of positive Bouguer anomalies. In the vicinity of the epicenters the gravity data indicates that the unit is perhaps thinner than to the northeast or southwest. Consequently, this zone would be more susceptible to high stress levels and earthquakes. This zone is also coincident with a northwest-southeast trending zone of

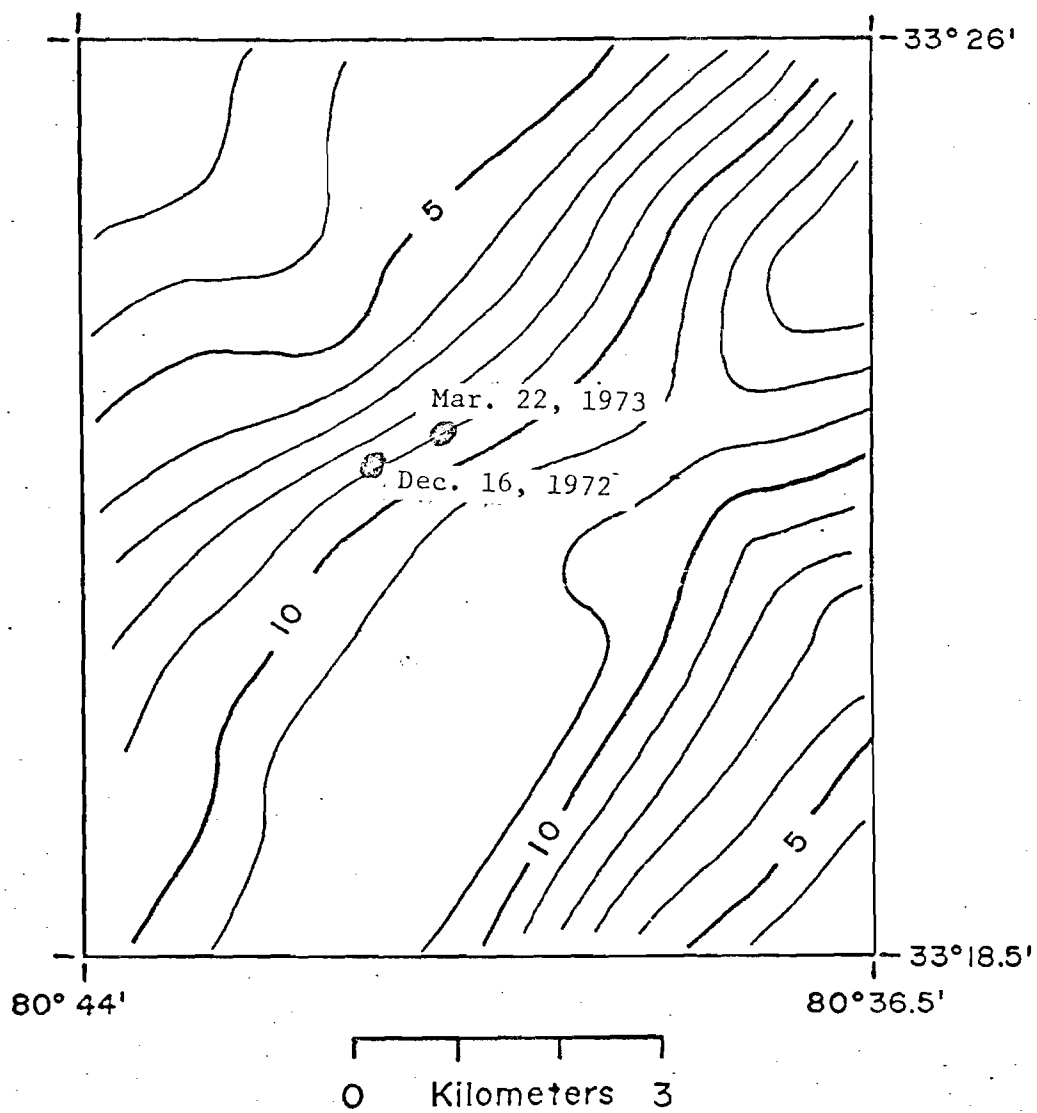


Figure 3. Linear positive Bouguer gravity anomaly near Bowman, South Carolina. Contour interval is 1.0 miligal. Microearthquake epicenters show association with thin zone in the interpreted dike-like structure.

perturbation in the contours of the Bouguer gravity anomalies indicating the existence of a boundary zone between coherent crustal blocks. Approximately two kilometers northeast of the epicenter, detailed gravity data along a line northeast-southwest indicates a possible fault or sharp change in density at the basement. If this is a measurable fault it would indicate past activities and a potential for future earthquakes in that zone. In total these data show that earthquakes near Bowman, South Carolina are associated with the junction between thinning (and hence weakening) of a rigid crustal unit and a possible boundary zone between two coherent crustal blocks. The occurrence of earthquakes can be explained by the reaction of this geometry to regional stress.

Further to the southeast an extensive zone of positive Bouguer anomalies exists near the epicentral zone of the 1886 Charleston earthquake (see Figure 4). Existing historic data strongly support an association between the seismicity and the high density unit in the crust. The epicenter of the November 21, 1974 earthquake (Dr. Pradeep Talwani, personal communication) falls directly on a gravity ridge extending from the gravity high to the east. The gravity here indicates a geometry similar to the interpreted geometry near Bowman.

The intensity IV earthquake in 1875 near Lincolnton, Georgia, is one of the few events in Figure 2 not obviously associated with a prominent gradient. Yet, this event is located on the west end of a metadacite unit exhibiting a 5 mgal positive gravity anomaly as interpreted from data not available during compilation of data in Figure 2 (Denman, 1974). Over 12 magnitude (m_b) 3.5 or smaller events have been recorded at regional seismic stations such as ATL, ORT, CPO, and BLA. These events were located within the general reservoir area. A variation in epicenter

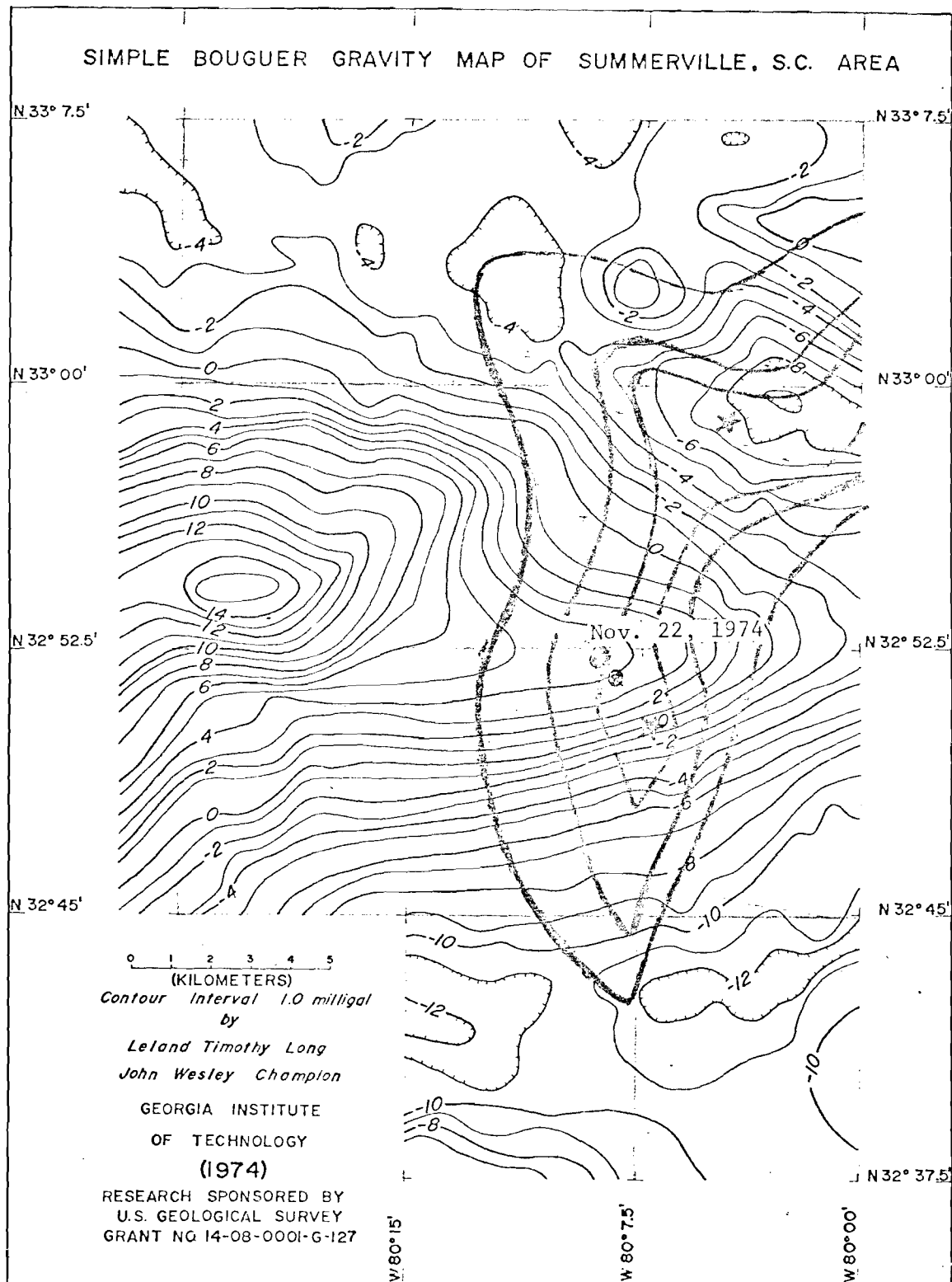


Figure 4. Simple Bouguer gravity map of Summerville, South Carolina area. Epicenter shows association of earthquakes with linear gravity high. Heavy lines are approximate isoseismal of the 31 August 1886 Charleston earthquake and stars are "epicentra" determined by Dutton (1889).

locations by at least 20 kilometers is indicated by variations in S-P times (Denman, 1974). Over 10 microearthquakes were recorded during a microearthquake survey of over 80 noise-free days. However, only one could be located uniquely and it occurred about 10 kilometers southeast of the presumed epicenter of the 1875 earthquake. The activity of the region is substantiated by the location of a magnitude 4.5 event approximately 20 kilometers north of Lincolnton on August 3, 1974.

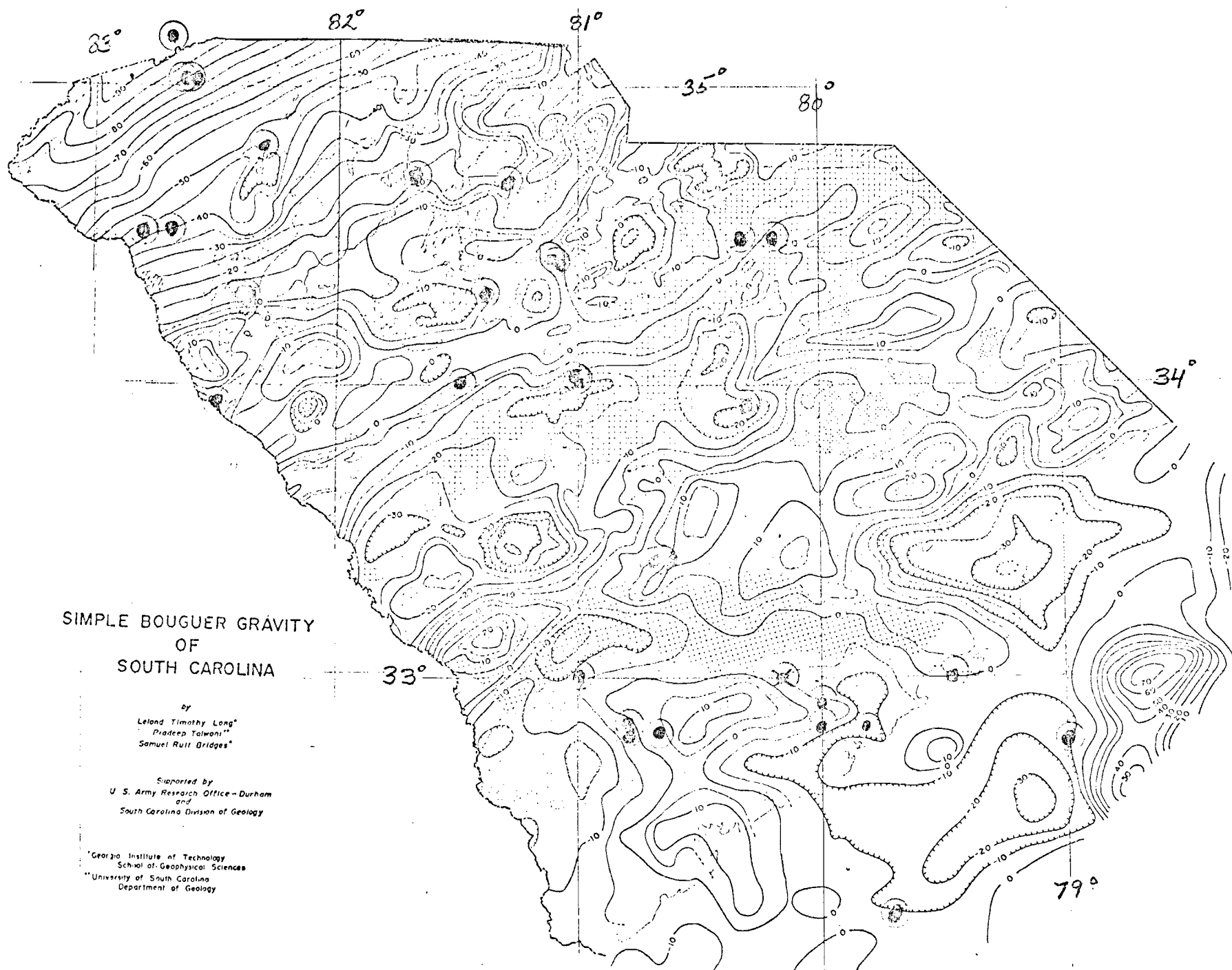
The metadacite unit has been interpreted as a sill and consequently would geometrically be similar to Figure 1b. In addition, the existence of other smaller basic and thus high velocity units throughout the region would explain the lack of a well developed gravity gradient and the variation in epicenters. Nevertheless, earthquakes in the Clark Hill Reservoir area can be associated with rigid units as would be expected from the working hypothesis. The epicenter of the one event recorded within a tripartite array occurred in the Button schist unit near the Little River. This unit exhibits evidence of extensive shearing and is characterized by its muscovite buttons and stringers of quartzite. This event may represent an exception to the hypothesis in that it does not occur associated with a more rigid unit (even though quartzite stringers exist in the unit and the event was smaller than $m_b = 0.0$). The existence of major shear zones of historic significance which trend parallel to the structure in the southeast has posed a major problem in interpreting the earthquake tectonics. Significant earthquakes in the southeast previously have not been associated with these faults. The faults represent low-strength zones in the crust which may be capable of movement. If analogous to contemporary active faults they are most likely capable of sustaining only low-level shear

stresses which would be on the order of 100 bars or less. The existence of events on these shear zones is not excluded by the hypothesis. Their role in the hypothesis is to impart a boundary condition of low shear stress levels on existing crustal blocks and consequently some movement should be expected. Stress levels in excess of 100 bars are observed in the more rigid crustal rocks like gneiss or granite in the southeast (Sbar and Sykes, 1973).

A general association of earthquake epicenters with rigid units as indicated by positive Bouguer anomalies can be seen in the Bouguer Gravity map of South Carolina (Figure 5). The Bowman and Charleston epicentral relations described above can be seen in other areas directly. However, the relation is more difficult to identify in the northwest part of South Carolina because of the regional gradient. However, even in these areas the contours are often perturbed in such a way as to indicate a positive residual anomaly. The hypothesis is in general supported by other associations indicated by the Bouguer anomalies even though the data are not as well qualified.

The strongest evidence for the validity of the hypothesized model for southeastern earthquakes is the association of events with the geometrically susceptible or weak zones of the more rigid geologic units. However, a number of other factors necessarily can contribute to the concentration of stress and hence the occurrence of earthquakes. The perturbation of stresses effected by boundaries between crustal units as previously mentioned can be extended in general to apply conceptually to lateral irregularities of the crustal structure within crustal blocks. However, internal lateral irregularities are not as easily identified as boundaries between coherent crustal blocks. In either case these

Figure 5. Simple Bouguer gravity map of South Carolina showing major geologic structures and earthquake epicenters.



are largely geometrical properties which in order to delineate would require detailed data not currently available.

The relative strengths of the crustal rocks must also be considered in evaluating the plausibility of the hypothesis for southeastern earthquakes. The existence of northeast-southwest trending Paleozoic shear zones which may be remnants of Benioff zones constitute significant contemporary zones of weakness and consequently they must limit the shear stress on their surface. Away from these zones the occurrence of earthquakes will be influenced by the contrast in shear strength between the more rigid rocks like the basic intrusives and the country rock which can be granitic or metasedimentary. The metasedimentary rocks are inhomogeneous in composition ranging from granitic to gabbroic. The strengths should be less than or equal to either the granite or basic rocks. The most significant difference in strengths with relevance to the hypothesis would be between a granite and a gabbro. While data on this are limited, Hadley (1973) presents data that indicate that granite and gabbro near zero confining pressure fracture at shear stresses of 2.0 to 5.0 kbar. The gabbro often showed the larger uncertainties and lower strengths. The data also indicate that the onset for dilatancy near the surface may occur at lower stress difference levels (about 0.5 kbar) in gabbro than in granite (about 1.0 kbar). Hence, not only will the more rigid rock unit be more capable of concentrating stress but it may also be more susceptible to dilatancy and fracture at lower stress levels. An increased probability of rupture and hence earthquakes with these gabbroic units is supported by data relating to their strength and behavior under stress.

Origin of Crustal Stress in the Southeast United States

According to the hypothesis, the geometries of rigid units in the earth's crust determine where earthquakes will most likely occur in the southeastern United States. However, to initiate the occurrence of earthquakes, stress must be applied to the structure. Because of the stress amplification by the geometry of the structures, earthquakes can be initiated by low-level regional or local stresses which normally would not be directly associated with earthquake occurrence. Consequently, it is not necessary to relate observed stresses to the relatively high strain rates which are observed at plate boundaries and which are responsible for most of the world's earthquakes. In contrast, the hypothesis allows the generation of high stress levels from mechanisms involving much slower strain rates.

Fletcher et al. (1974) noted an association of crustal and upper mantle structures characterized by high seismic velocities with the South Carolina and Ottawa seismic trends which occur along landward extensions of fracture zones active in the early opening of the Atlantic. This association, in light of the hypothesis for the southeast United States implies that geometrically appropriate structures were formed at that time and/or the mechanism of separation in the region of these fracture zones was such as to generate residual stresses. Undoubtedly, the existence of Triassic basins and their associated volcanic rocks and basic intrusions may be responsible for many of the geometries of the structures responsible for recent earthquakes. However, age perhaps is not as important a criteria as the geometry of the more rigid structures. Studies modeling the thermal-elevation response of a hypothetical model of southeastern United States crustal structure (Long and Lowell, 1973)

indicate a short term duration less than four million years for the significant thermal perturbations of surface elevation. Longer term variations were of regional character or would be caused by a perturbation of the system by other factors like sediment loading. Hence the existence of residual stress cannot alone explain the occurrence of earthquakes unless they are perturbed by stresses from a contemporary source. Furthermore, it is questionable that significant stress loads could be sustained for time periods on the order of 100 million years.

The model of Long and Lowell (1973) showed that a sedimentary blanket over extended time periods could perturb the thermal gradient and result in uplift. Sediment thickness data for south Georgia (Cramer, 1974) indicates that subsidence following the genesis of the Atlantic was not uniform in the southeast and distinct blocks of crust were perhaps reacting independently to sediment loading. Over a long period of time the different sediment thickness could influence the thermal gradient and elevation of the individual blocks. In south Georgia the post-Cretaceous sediments are generally divided into an east and west depositor by the central Georgia uplift. The uplift corresponds approximately to a northwest-southeast zone of gravity anomalies (Long, 1974) which can be interpreted as the contact zone between two crustal units. Isopach data from Cramer (1974) indicate more rapid deposition and hence possibly more rapid subsidence on the southwest crustal block from Cretaceous to Middle Eocene time. Following the Middle Eocene, deposition and hence possibly subsidence was more rapid on the southeast Georgia block. The sediment thickness data and their surface contours are evidences of the existence of types of crustal movement capable of generating regional stresses, particularly near the edges of two coherent blocks.

Earthquakes in Georgia have occurred along this trend near its intersection with the fall line and near the northwest corner of Georgia. The remaining Georgia earthquakes have occurred along the Georgia-South Carolina border with only a few questionable exceptions.

Apart from the occurrence of earthquakes in Georgia, contemporaneous evidence of vertical crustal movement can be seen in releveling data (Meade, 1971) which shows probable annual rates of vertical crustal uplift as fast as 7 mm/yr. A correlation of the uplift data with free air gravity anomalies (Long, 1974) indicates that isostatic response can be the underlying cause of the uplift in Georgia. Bollinger (1973) has noted a general correlation of the seismicity of the southeast United States with the relatively narrow zones of differential uplift which would correspond to zones of maximum crustal curvature. Bollinger further conjectured on the basis of the general correlation that strain development induced by crustal uplift but concentrated by old Appalachian structures is the proximate cause of recent seismicity in the southeastern United States.

Isostatic response perhaps driven by sediment loading or unloading and thermal perturbations exists in the southeast and can explain the observed uplift and strain accumulations necessary to initiate the occurrence of earthquakes at the geometrically appropriate points in more rigid crustal units. However, near a boundary between different crustal blocks or near topographic irregularities on the Moho, exact isostatic equilibrium cannot be complete (Artyushkov, 1974) and secondary perturbing stresses will exist. Thus incomplete isostatic equilibrium near crustal boundary zones and topographic irregularities of the Moho can influence the occurrence of earthquakes in the more

rigid structures near these features. The epicenters of the earthquakes in central Georgia are perhaps determined by isostatic forces of this type.

The stresses derived from isostatic rebound or incomplete isostatic equilibrium are sufficient to explain the occurrence of earthquakes in the southeast United States when coupled with the geometrical amplification of stresses by more rigid structures. However, stresses related to other mechanisms may also exist and contribute to the seismicity. Sbar and Sykes (1973) proposed a relatively simple stress model for the eastern portion of North America. Using data obtained from geological observation, in-situ stress measurements and fault-plane solutions, they concluded that the central United States is presently experiencing a predominantly horizontal compressive stress whose axis tends east-northeast. This simple uniform stress could be geometrically amplified in a manner similar to the isostatic stresses and could similarly explain the occurrence of earthquakes in the more rigid structures. However, to be effective in actuating earthquakes the uniform stress would have to be either a time-varying stress or be perturbed by other local stresses. Also, ongoing earthquake activity should be mostly of the high-angle, thrust-type faulting with a strike in the north-south direction. However, in the central United States, earthquake mechanisms indicate a more complex stress distribution (Street, et al., 1974) which would be more compatible with the hypothesized isostatic stresses in the southeast United States. The effects of a weak uniform stress could probably not be distinguished from the effects of locally derived stresses without direct measurement. The scatter in the source mechanism in central United States and the northwest-southeast trends in seismicity in the

southeast United States indicate that if a uniform stress field exists it must be weak or less influential than stresses derived from isostatic adjustment.

Stresses derived from the movement of an irregular thickness of the north American plate over a viscous upper mantle could also perturb the isostatic stress distribution. These stresses would be difficult to distinguish from the incomplete isostatic equilibrium stresses expected near Moho topographic irregularities and boundaries between different coherent crustal blocks since they would be strongest where crustal structures protrude into the mantle.

If traced along the direction of the presumed movement of the North American plate (see Solomin and Sleep, 1972) the Charleston, South Carolina seismic zone intersects the Smokey Mountain mass which is perhaps the largest mountain mass east of the Rocky Mountains. The stresses responsible for some of the activity in the seismic zone could be partially derived from local upper-mantle readjustments to the moving displacement of the upper mantle caused by the mass of the Smokey Mountains. Seismic activity exists along the entire southern Appalachian Mountains further indicating a potential response to viscous drag stresses. Uniform regional stress or viscous drag stress would be difficult to distinguish from stresses derived from isostatic rebound. Furthermore, if they exist they are probably related directly or indirectly to the tectonic mechanisms responsible for the perturbation of isostatic equilibrium. In the opinion of the author, primary origin for the crustal stresses which actuate earthquakes in the southeast United States is most likely the isostatic response to crustal loading, unloading or thermal perturbation. These stresses may also be

modified by uniform regional stresses perhaps derived from plate edge effects and viscous stresses related to movement of the North American plate.

Implications and Potential Application of the Hypothesis

The hypothesis, perhaps for the first time, allows identification of specific structures in the southeastern United States which are responsible for earthquakes. It implies that the Charleston 1886 event could only occur near Summerville and that it is improper to attempt to "propagate" it along some hypothetical fault. However, other similar areas, like Bowman, exist in the southeast and may pose a comparable seismic risk. The location of most of these areas could be found by conventional seismic, gravity and magnetic geophysical exploration methods. The maximum potential earthquake could be estimated by a geometrical modeling of the structure and its possible reaction to applied stresses. Microearthquake monitoring could be utilized to identify the susceptible zones in which stress levels are approaching a critical level. Releveling data could be used to indicate strain rates in the crust and zones of maximum possible stress accumulation.

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